Next Generation LF Transmitter Technology for (e)LORAN Systems

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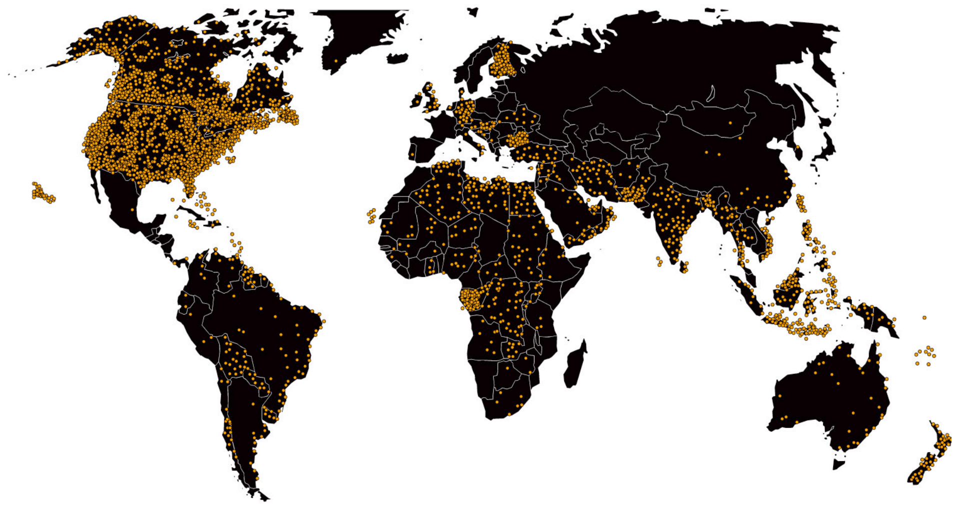
Who are we?

Nautel is: A designer and manufacturer of:

- Solid State NDB and DGPS Transmitters
  +3,600 units since 1970
- Solid State MF Telegraph Transmitters
  +200 units since 1970
- Solid State VHF – FM Broadcast Transmitters
  +1200 units since 1992
- Solid State MW – AM Broadcast Transmitters
  +2,700 units since 1982
- Customers include:
  – FAA, USCG, CCG, ASA
  – CBC, ABC, Clear Channel, NGW, FEBC, TWR
  – and many others …

Installed Base



Making Digital Radio **Work.**

Overview

- The Challenge Of Loran Transmission
  - Antenna System Analysis
  - Pulse Transient Analysis
- Transmitter and Class D Amplifier Theory
- Antenna Power Recovery
- Proof of Concept Transmitter
- Conclusions
- Thoughts on Short Antennas
- Future Work

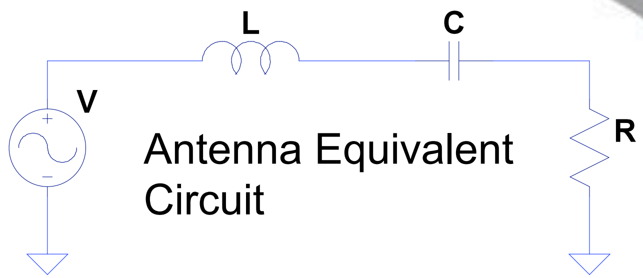
The Challenge of Loran Transmission

- Can we use a more general “amplifier like” system for transmitting Loran?
- To answer, an understanding of typical Loran antennas is required:
  - Loran is transmitted at a frequency of 100 kHz.
  - λ/4 antenna would be 750 metres tall – not practical.
  - A common antenna is the 625’ TLM – only 190m or 6% of λ.
  - This is a short antenna – high Q and narrow bandwidth.
- We need a quantitative analysis of antenna bandwidth and its effect on the transmitted signal.

$$BW = \frac{f_c}{Q}$$

Antenna System Analysis

- A series RLC lumped constant equivalent circuit is used to model the antenna system.
- Antenna base measurements of impedance ($R + jX$) and reactance slope ($dX/d\omega$) are made.
- Equivalent circuit component values can be determined from base impedance measurements.
- Antenna response can be determined from the antenna equivalent circuit.



Antenna Equivalent Circuit

$$C = \frac{2}{\omega^2 \frac{dX}{d\omega} - \omega X}$$

$$L = \frac{1}{2}\left(\frac{dX}{d\omega} + \frac{X}{\omega}\right)$$

625’ Top Loaded Monopole

Antenna Base Measurements:

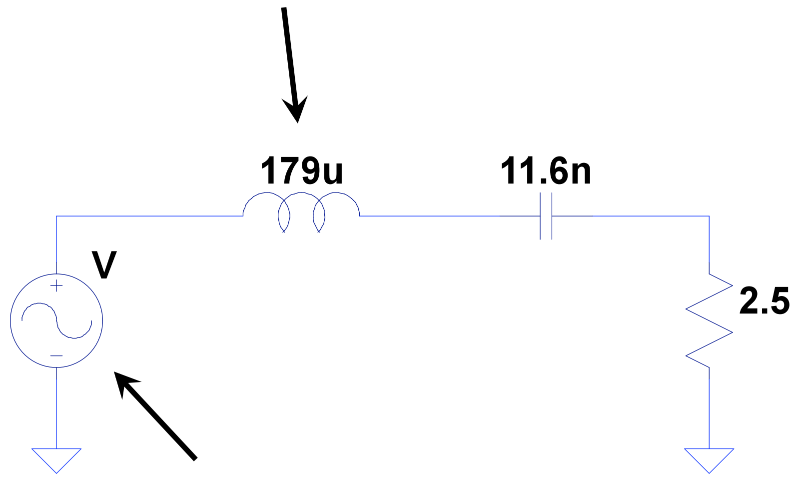
Base Impedance:	2.5 – j 25 ohms
Reactance Slope:	+ 2.5 ohms/kHz

Equivalent Circuit:

Resistance:	2.5 ohms
Capacitance:	11.6 nF
Inductance:	219 µH*
Q:	55
BW 3dB:	1818 Hz

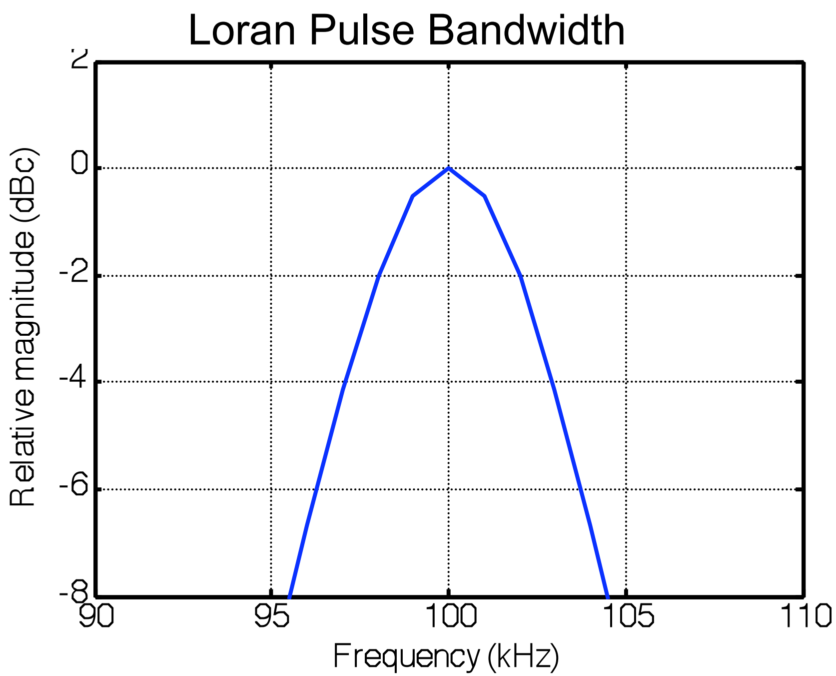
* Additional 40 µH required for resonance at 100kHz

Increased to 219 µH to adjust resonance to 100kHz

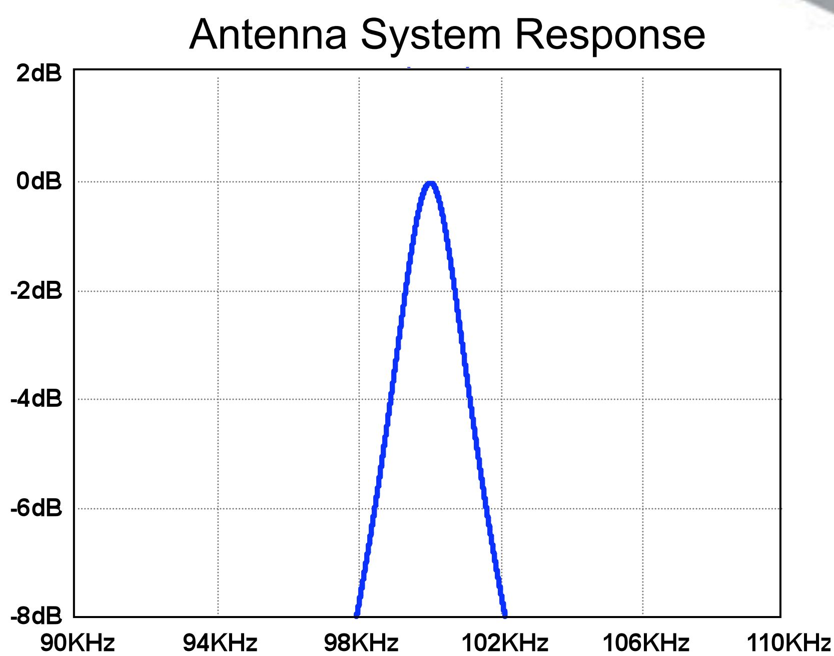


What voltage waveform is required to generate Loran current waveform?

625' TLM Bandwidth Deficit



3dB BW = 5 kHz

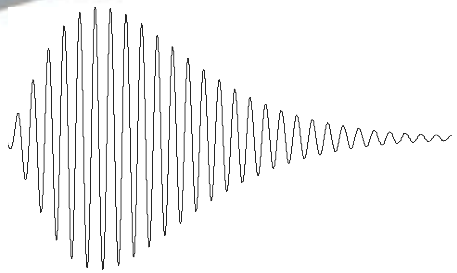


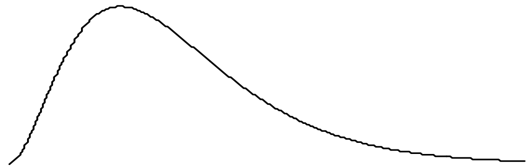
3dB BW = 1.8 kHz

Making Digital Radio **Work.**

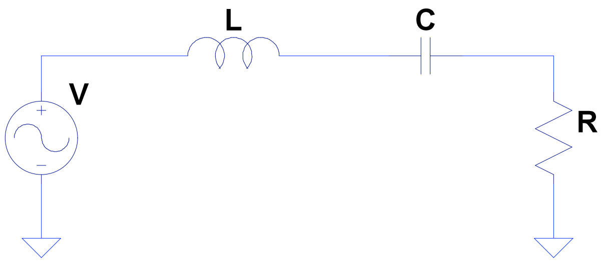
Simplified Transient Analysis

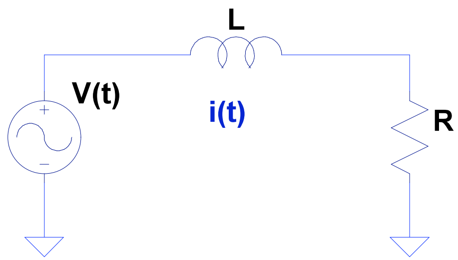
Lowpass Transformation





$$i(t) = t^2 e^{-at} \sin(0.2\pi t) \longrightarrow i(t) = t^2 e^{-at}$$





Network equation

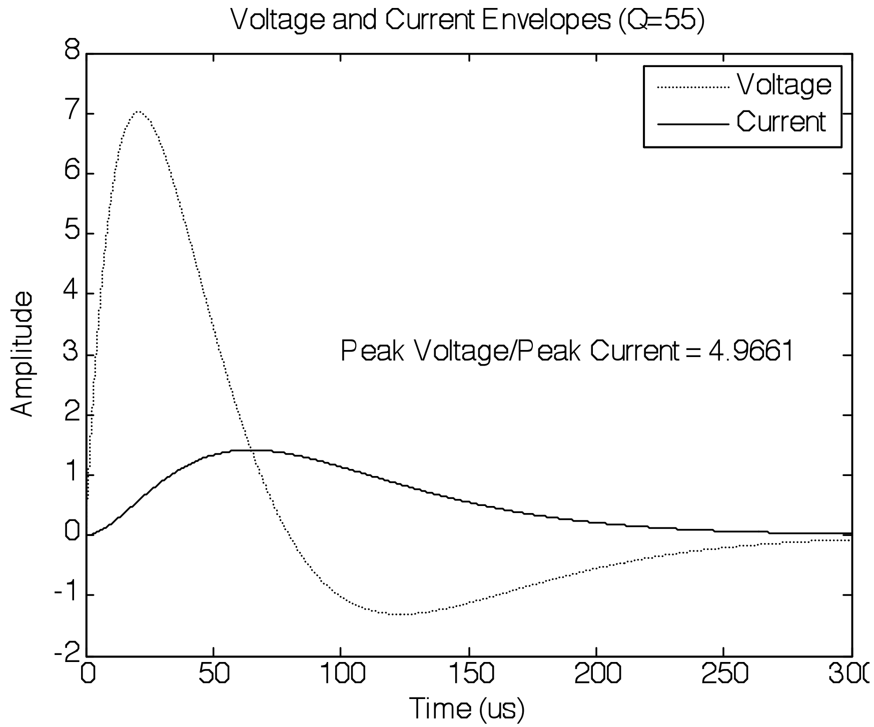
$$V(t) = i(t)R + L\frac{di}{dt}$$

Source voltage required for Loran current pulse

$$V(t) = (2Lt - aLt^2 + Rt^2)e^{-at}$$

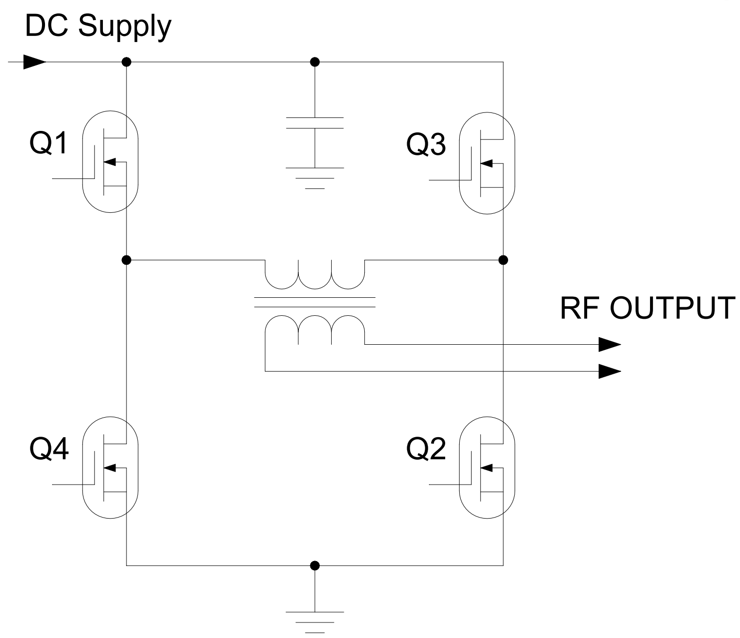
Pulse Transient Analysis - Result

- Voltage waveform is very different from the current waveform.
- Widely varying impedance would be problematic for conventional transmitters.
- Voltage peak is 5x current peak - practical ramification is that a Loran transmitter needs to source 5x higher voltage than would be expected with a broadband antenna.
- Current and voltage in opposition representing negative power flow.



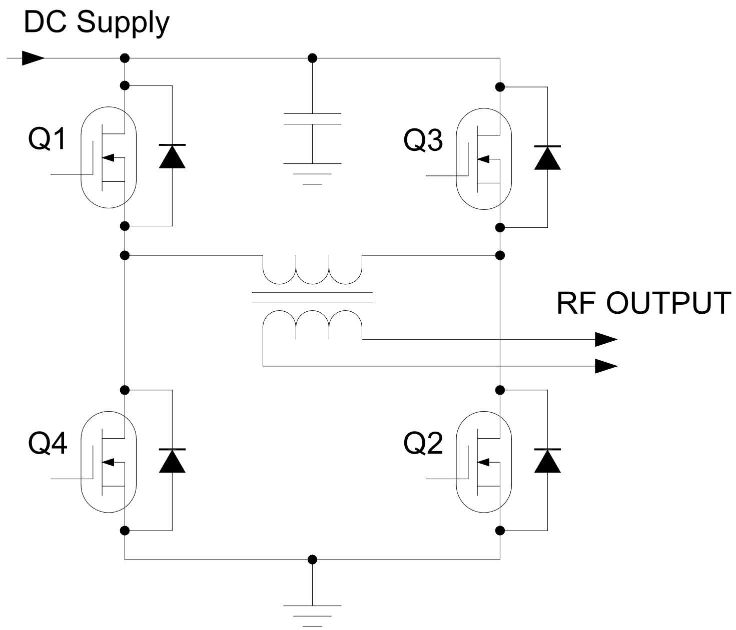
Class D Amplifier

- Switch mode amplification: Ideally transistors are always either in a zero current or zero voltage mode. No power is dissipated.
- Operates as a voltage source.
- RF Class D will switch the transistors synchronously with the RF current, once per RF cycle at optimal time to minimize losses related to switching.
- DC to RF Efficiency > 98% and power levels > 10 kW are practical at 2 MHz and below with latest devices.
- May be operated in driving or disabled modes to achieve AM with many amplifiers.



Antenna Power Recovery

- An new mode of amplifier operation recovers power from the antenna during negative impedance portion of the pulse.
- Diodes are installed in reverse across the transistors.
- Amplifier returns rectified antenna current to the power supply decoupling network.
- Allows amplitude modulation with negative voltage terms.
- Significant improvement in system efficiency when compared to damping excess energy in a resistor bank.



Effect of Power Recovery

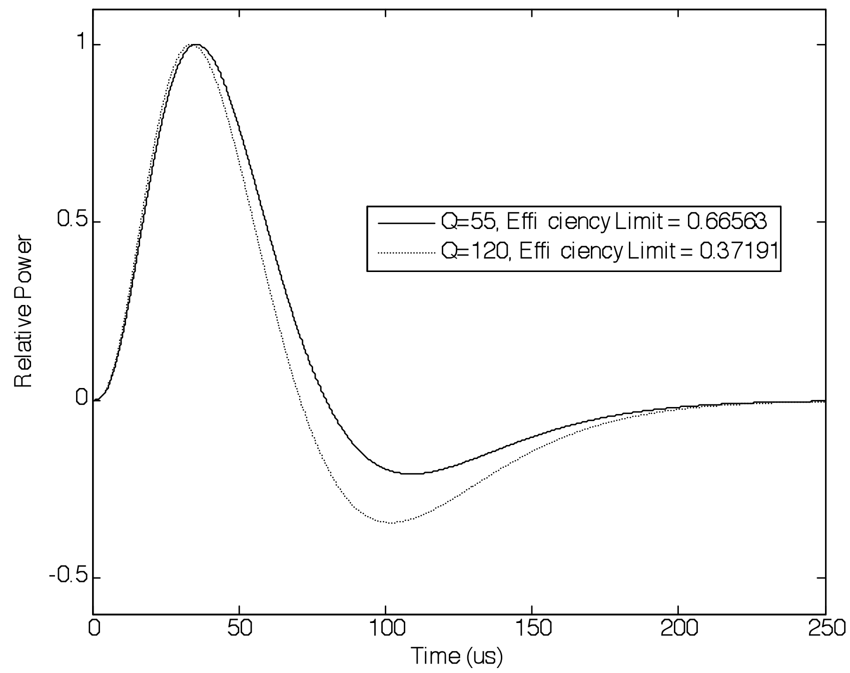
- An efficiency factor can be determined representing the limit of efficiency that a transmitter without power recovery is limited by:

$$\eta_{MAX} = \frac{E_S - E_R}{E_S}$$

- E_S is the energy that flows to the Antenna in the first half of the pulse.
- E_R is the energy that flows to the Transmitter in the second half of the pulse.

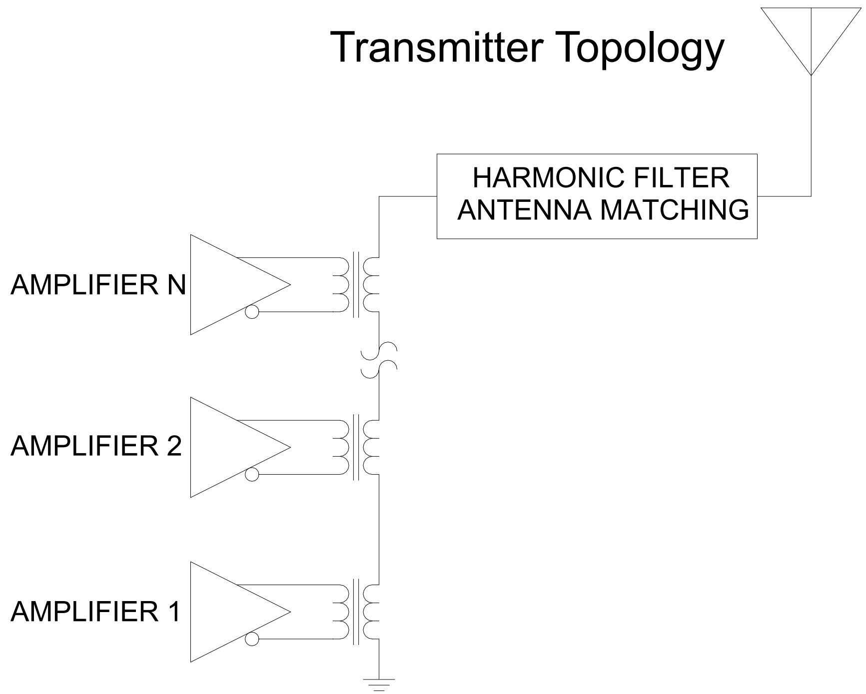
- For Q = 55: η_{MAX} =67% (1.5x AC power)
- For Q = 120: η_{MAX} =37% (2.7x AC power)

Power Envelope (V x I)



Transmitter Topology

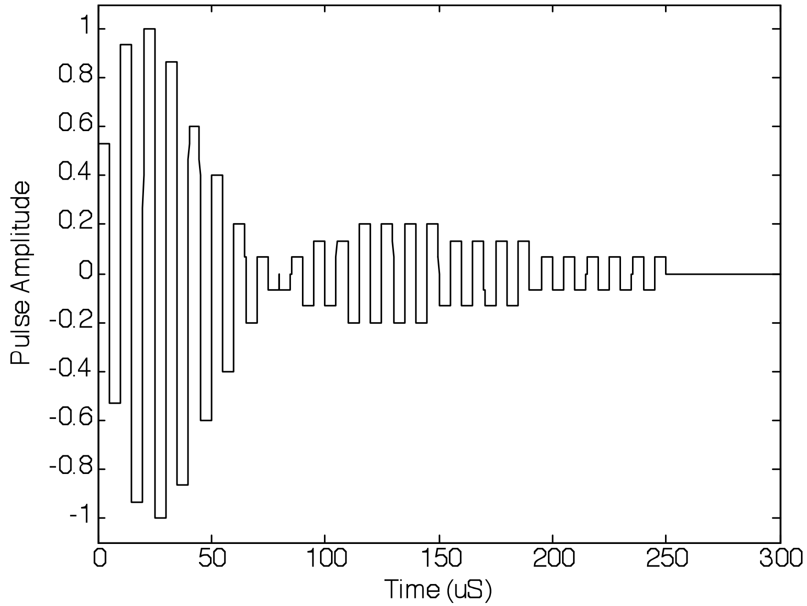
- 10 or more amplifiers are required to generate requisite power levels and provide AM modulation capability.
- A transformer for each amplifier with a common secondary connection combines the voltages and powers of the individual amplifiers.
- A harmonic filter prevents harmonic voltages at the amplifier output from inducing antenna harmonic currents.
- An antenna tuning and matching network would resonate the antenna circuit at 100kHz and match impedance to different antennas.



Transmitter Modulation

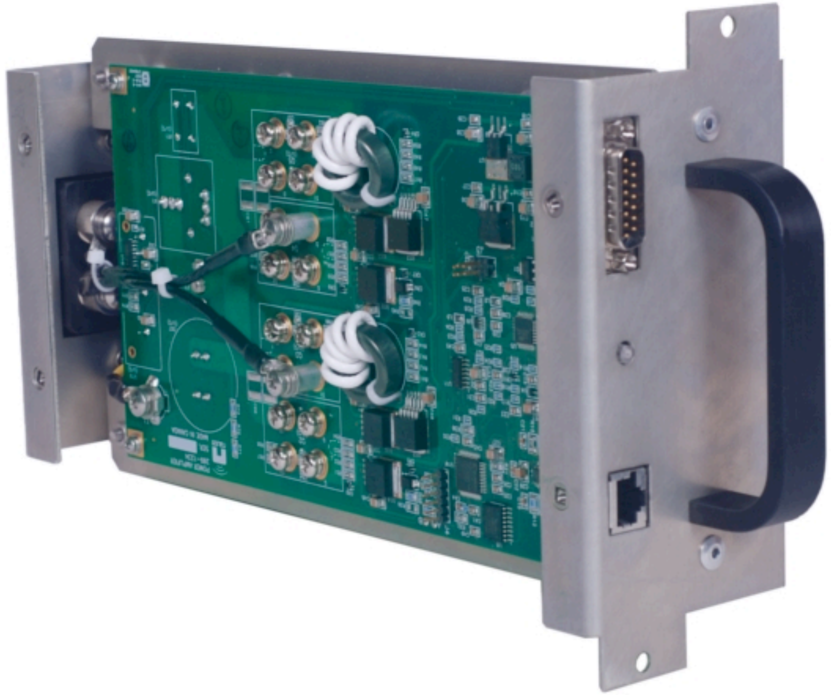
- Any source voltage waveform can be synthesized within the peak voltage limit of the transmitter.
- The modulation waveform must be separated into RF phase and Amplitude terms.
- Amplitude modulation is accomplished by determining the number of amplifiers to be driving the antenna on each RF cycle.
- Phase modulation is accomplished by adjusting the times at which the RF amplifiers switch.
- Loran pulse sequence on 15 amplifiers: 8, 14, 15, 13, 9, 6, 3, 1, -1, -2, -2, -3, -3, -3, -3, -2, -2, -2, -2, -1, -1, -1, -1, -1 and -1.

Combiner Output Voltage



Proof of Concept - Amplifier

- Prototype amplifier and combiner section were developed for 100kHz operation, September 2007.
- Test bed with high Q antenna simulator was constructed.
- Design goals of peak power and efficiency were achieved.
- Power recovery was demonstrated.
- Transmitter design began.



Proof of Concept Transmitter

- Proof of Concept Transmitter was built to validate the theory presented in this paper.
- Transmitter Specifications:
  - 50 to 100kW Loran pulse capable
  - 600 pps
  - DSP based exciter
  - 15 Amplifiers + 1 standby
  - 2 Tail “Nibblers”
  - Hot Serviceable Amplifiers
  - Manual Antenna Tuning capability
- System was installed and operational with 1/2 days.
- Operation was into a 625’ TLM.
- The transmitter has performed as expected.

Conclusions – Class D Advantages

Flexibility: The transmitter is a voltage source and can synthesize a wide range of signals. Operation with very short and high Q antenna systems is possible.

Efficiency: The Class D amplifier is very efficient and is capable of recovering power from the antenna dramatically boosting overall system efficiency.

Scalability: Low to Multi-megawatt power levels are practical.

Robustness: The system is extremely fault tolerant. The signal can be maintained within specification with 25% or more amplifier failures.

Accuracy: Very low pulse to pulse jitter and tight pulse to pulse amplitude variations have been demonstrated.

Reliability: Class D amplifiers are simple robust devices that have a proven reliability record during 40 years in high power RF applications.

Thoughts on Short(er) Antennas

- Is it possible to transmit Loran with short (say 20m – 100m) antennas?
  - Normally the transmitter efficiency would be very low, however the power recovery technology described here mitigates that problem.
  - Low radiation resistance lowers antenna efficiency. However efficiency can still be acceptable if careful design is used to minimize conduction loss in the structure and ground return.
  - Low radiation resistance requires higher current to generate power. This current must then flow in the antenna capacitance and inductance generating high voltages. So to achieve higher power levels, high voltage levels will be required. This will likely be the limiting factor.
- So yes, short antennas may be used however power levels will be reduced.
- Short antennas could still be a useful solution for smaller coverage areas, harbour entrances, tactical systems etc. Further work is required to determine the limits of "short" practical antennas for (e)Loran.

Future Work

- Nautel is currently developing Loran transmitter products based on the technology described here.
- The transmitters will be scaleable by changing the number amplifiers. Power levels from a few kilowatts to more than 2 megawatts or more will be practical.
- The design emphasis is on simplicity as well as parallel redundancy to achieve the highest possible system availability.
- Nautel uses adaptive digital pre-correction systems on our broadcast transmitters. These systems use DSP to “close the loop” and should offer the benefit of stable timing and automatic “tuning” of the transmitter voltage waveform for the antenna system used.
- An IP connected control, diagnostic and measurement system will be added.

Thank You!

Questions?